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A THERMOELECTRIC POWER GENERATOR CONCEPT FOR USE IN SMALL CALIBER MUNITIONS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (hib) A thermoelectric power supply concept was evaluated. The concept involved using the heat generated when a round is fired as the input heat to a direct conversion module to produce electrical energy. Open circuit voltages as high as 8 volts were recorded. These voltages were obtained under simulating firings of 30 mm rounds. A thermoelectric power supply using hot propellant gages is definitely feasible.

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I. INTRODUCTION

Integral to any warhead is the fuzing system or device. This device is used to accomplish several functions. These are: (1) initiate the explosive train within the warhead leading to the detonation of its high explosive charge; (2) allow for safe handling of the round prior to its launch and then arming the warhead after launching; (3) detect its environment to allow for detonation of the warhead at the proper time and under the optimum conditions. The fuze therefore plays an important and exacting role in warhead performance. Proper choice and functioning of the fuze gives rise to a highly effective warhead while an inappropriate choice or malfunction of the fuze can seriously reduce the effectiveness of the warhead even to the point of the warhead being a dud.

Fuze research at the Ballistic Research Laboratory, (BRL) has been principally directed at munitions employing shaped charge warheads. These warheads utilize impact-type fuzes which function in a super-quick time mode, i.e. their functioning time is of the order of 100 microseconds (μs) or less. The basic objectives of the BRL effort were to improve the performance of the warhead through improved fuze functioning and to provide the warhead with a full frontal area impact sensitivity capability.

To meet these objectives a unique fuze system was devised[1,2]. The information signal, caused by the impact of the warhead, is sent to the detonator by means of a light pulse that causes the detonator to function. Operation of the fuze is relatively uncomplicated. The inside of the warhead's ogive is coated with a triboluminescent phosphor[2,3]. This phosphor posses the ability to emit light whenever the crystal structure is mechanically disrupted which occurs under impact conditions. Use of this phosphor permits the entire ogive surface to function as an impact sensor thereby satisfying our second basic objective of providing full frontal area impact sensitivity. A photo-detector which is a light activated silicon controlled rectifier (LASCR), is mounted in the apex of the shaped charge liner. This device senses the light pulse generated upon impact and is switched on. This switching action permits a previously energized capacitor to discharge through the detonator. This starts the

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[1] *Glass, C. M., Dante, J. G., Cialella, C. M. and Golaski, S. K., "An Electro-Optical Fuze System", BRL MR No. 2552, October 1975.* (AD #B008043L)

[2] *Glass, C. M., Dante, J. G., "Light Activated Fuze", Patent No. 4,020,765.*

[3] *Leverenz, H. W., "Luminescence of Solids", John Wiley & Sons, Inc., Somerset, N. J., (1950).*

initiation sequence leading to detonation of the warhead. This fuze was successfully demonstrated in live firings with the M72 LAW round serving as test vehicle.[4] Efforts are currently under way to adapt this fuze to other shaped charge warheads.

In the test firings of the LAW round, the capacitor was charged by an off-board power supply. Efforts are being made to provide on-board power through use of such devices as thermal batteries and electromagnetic generators. These devices can be incorporated in large caliber munitions fairly easily. Such, however, is not the case for small caliber, 20-40mm, munitions due to their size and weight limitations.

These small caliber rounds generally employ Point Initiating (P.I.) impact type fuzes. Basically, a pin is driven into a suitable explosive to start the initiation sequence. There has been some effort made to utilize piezoelectric generators in these rounds. In general, however, there is no electrical power available in small caliber rounds.

The need for an active power supply for small caliber munitions is readily apparent. By developing such a power source and combining it with the triboluminescent fuze a completely self-contained fuze system could be obtained. Such a fuze system would have a much wider range of application.

Within each round there is available an untapped primal energy source. This source is the thermal energy associated with the burning propellant and its gaseous by-products during the accerleration of the round in the gun tube. By converting this thermal energy, or at least some portion of it, to electrical energy a source of power can be made available. This energy could be stored in a capacitor and used to detonate the warhead at a later time. If the conversion process could be maintained over the projectile's time of flight to its target an active power source would be available within the warhead to operate various electronic circuits, such as timing circuits and detection circuits.

This report describes the design of a thermal conversion power supply, or thermoelectric module. Results of the feasibility tests conducted with the module are also presented.

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[4] *Glass, C. M., Dante, J. G., Cialella, C. M. and Golaski, S. K., "A Light Activated Fuze System", BRL MR No. 2726, February 1977.* (AD# B017049L)

II. BASIC RELATIONSHIPS OF THERMOELECTRIC POWER GENERATION

A. Direct Conversion

The most efficient means of converting the thermal energy generated when a round is fired is through direct energy conversion. By eliminating any intermediate mechanical device, the power supply module can be designed very simply with a minimum of weight. This would also serve to keep the module's cost down.

A schematic of such a direct conversion module is shown in Figure 1. The main elements of the device are composed of n-type and p-type semiconductor materials which are joined at the hot junction by a metallic connecting strip. The external circuit is connected across the cold junctions of the individual elements. By using n-type and p-type conductors the output current is maximized. This type of device is, therefore, a high current low voltage unit. Thus, by combining several of these devices so that their elements are in parallel and/or series it is possible to produce a wide range of output voltages and currents.

B. Efficiency

In any thermal conversion device, efficiency is of primary concern. For a power supply the efficiency is expressed as the ratio of the useful electrical energy delivered to the external circuit to the energy absorbed from the heat source.[5] This ratio is expressed by

$$\eta = \frac{I^2 r_L}{Q_1 + Q_2 - 1/2\ I^2 r_{int}} \qquad (1)$$

where η = efficiency
I = current (ampere)
r_L = external resistance (ohm).
Q_1 = Peltier Heat (watt)
Q_2 = Heat transfered by conduction to cold junction (watt)
r_{int} = internal resistance (ohm)
$1/2\ I^2 r$ = Joule heating lost (watt)

[5] *Egli, P. H., "Thermoelectricity," John Wiley & Sons, Inc., New York and London, 1960.*

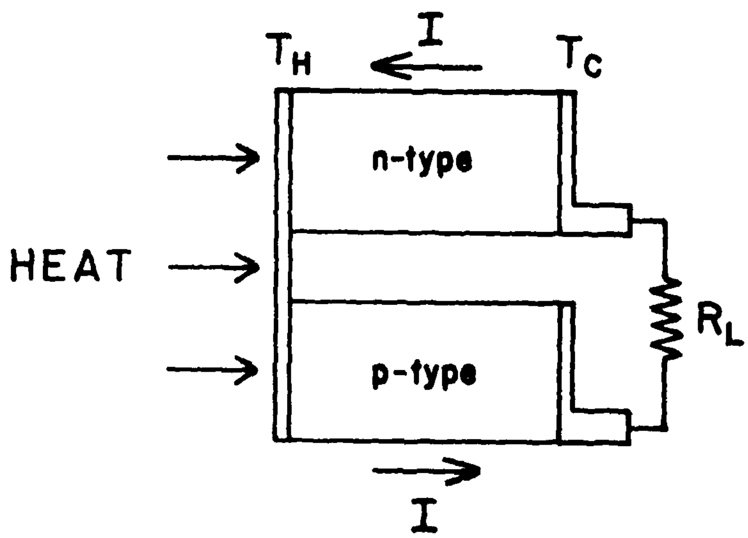

Figure 1. Direct Conversion Module.

Ioffe[6] has shown that the efficiency of a thermoelectric device is dependent upon (1) the hot and cold junction temperatures (2) the internal resistance of the device and the resistance of the external circuit and (3) is a quantity "Z" called the Figure of Merit. This quantity "Z" he used to express the relationship between the Seebeck coefficient of the material, its resistivity and its thermal conductivity. He expressed this relationship as

$$Z = \left[\frac{\alpha}{(K_p\rho_p)^{1/2} + (K_n P_n)^{1/2}}\right]^2 \qquad (2)$$

Where Z = figure of merit (deg^{-1})
α = Seebeck coefficient (volt/°C)
K_p = thermal conductivity of p-type material (watt/°C - meter)
ρ_p = resistivity of p-type material (ohm-meter)
K_n = thermal conductivity of n-type material (watt/°C - meter)
ρ_n = resistivity of n-type material (ohm-meter)

The figure of merit permits the effectiveness of any material to be determined for use in a thermoelectric device based on the properties of the material and not its dimensions. As derived by Ioffe, the efficiency becomes

$$\eta = \frac{T_H - T_C}{T_H} \times \frac{(1 + Z\overline{T})^{1/2} - 1}{(1 + Z\overline{T})^{1/2} + T_C/T_H} \qquad (3)$$

where η = efficiency
T_H = temperature of hot junction (°K)
T_C = temperature of cold junction (°K)
$\overline{T}$ = average temperature $\left(\frac{T_H + T_C}{2}\right)$ (°K)
Z = figure of merit (deg^{-1})

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[6]*Ioffe, A. F., "Semiconductor Thermoelements and Thermoelectric Cooling", INFOSEARCH LIMITED, London. 1957.*

As "Z" approaches infinity this expression reduces to the familiar Carnot efficiency; $\frac{T_H - T_C}{T_H}$

C. Open Circuit Voltage

Once having made a choice of material for the thermoelectric module its voltage capabilities must be determined. For practical applications, the open circuit voltage is determined by the Seebeck coefficient of the material and the temperature difference between the hot and cold junctions. This is expressed as

$$V_{OC} = \int_{T_C}^{T_H} \alpha_T \, dT \tag{4}$$

where V_{OC} = open circuit voltage (volt)

α_T = Seebeck coefficient ($\alpha_p + \alpha_n$) (volt/°C)

T_H = temperature of hot junction (°K)

T_C = temperature of cold junction (°K)

If the assumption that the Seebeck coefficient is independent of temperature is made this expression reduces to simply

$$V_{OC} = \alpha_T (T_H - T_C) \tag{5}$$

D. Power

The power which the module will be capable of delivering will depend upon the open circuit voltage and its own internal resistance as well as the external resistance of the circuit. This can be expressed as

$$p = \frac{V_{OC}^2}{R} \tag{6}$$

where p = power (watt)

V_{OC} = open circuit voltage (volt)

R = resistance ($r_{int} + r_L$) (ohm)

By matching the internal and external resistances ($r_{int}=r_L$) maximum power can be transfered.

Equation (6) then becomes

$$p = \frac{V_{OC}^2}{2\, r_{int}} = \frac{\left[\alpha_T (T_H - T_C)\right]^2}{2\, r_{int}} \tag{7}$$

The internal resistance of the thermoelements is determined by their length, cross-sectional area and resistivity. This is expressed as

$$r_{int} = \frac{L}{A} (\rho_n + \rho_p) \tag{8}$$

where r_{int} = internal resistance (ohm)

L = length (cm)

A = area (cm^2)

ρ_n = resistivity of n-leg (ohm-cm)

ρ_p = resistivity of p-leg (ohm-cm)

A correction factor is necessary due to the variation of the resistivity with temperature. While the assumptions made in the foregoing theoretical evaluation were extremely broad, the equations which were developed will enable one to design and build a practical thermoelectric module.

III. DESIGN CRITERIA

A. Environment

When a round is fired the environment created within the cartridge case in the first several milliseconds can be classified as extreme.

Temperature values may reach as high as 1000° Kelvin and the pressures may extend well into the hundreds of megapascals (MPa).[7,8,9] With the wide choice of ammunition, it is necessary to quantify the environmental conditions relative to a particular round so as to be able to test the thermoelectric module. The environment associated with the firing of the M552 High Explosive Dual Purposed (HEDP) 30mm round was selected to be the test environment. The cartridge characteristics of this round which are of interest are the nominal operating pressure of 190-210 MPa, and cartridge action time of 3-4 milliseconds. The temperature would be determined under the actual test conditions.

B. Performance

The electrical characteristics which the thermoelectrical device should possess will depend upon its intended use. For these investigations the only consideration is that the device be capable of providing sufficient power to charge a capacitor. This capacitor would then be used to supply the needed energy to initiate a detonator in future testing.

From the wide assortment of detonators from which to choose, the Electric Bridge Wire (EBW) detonator was selected to establish the voltage requirements. This class of detonator has an internal resistance ranging from 0.75 to 10 ohms. The energy required to initiate this type of detonator varies from 500 to 5,000 ergs.

We can determine the voltage requirement for the module from the following expression

$$E = 1/2\ CV^2 \tag{9}$$

where E = energy (joule)
C = Capacitance (farad)
V = voltage (volt)

Using an assigned value of 1.5 microfarad (μfd) [1.5×10^{-6} farad] for the capacitor and establishing our energy requirement at 500 ergs (5×10^{-5} joule) as a minimum, this expression yields approximately 8.2 volts as the necessary voltage to satisfy our energy condition.

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[7] *Bannister, E. L., Jones, R. N. and Bagwell, D. W., "Heat Transfer, Barrel Temperatures and Thermal Strains in Guns", BRL Report No. 1192, February 1963.* (AD #404467)

[8] *Brosseau, T. L., "Development of the Minihat Pressure Transducer for Use in the Extreme Environment of Small Caliber Gun Barrels", BRL MR No. 2072, November 1970.* (AD #878325)

[9] *Brosseau, T. L., "An Experimental Method for Accurately Determining the Temperature Distribution and the Heat Transferred in Gun Barrels", BRL Report No. 1740, September 1974.* (AD #B000171L)

IV. MODULE CONSTRUCTION

Several materials possessing good thermoelectric characteristics were available for constructing the power supply module. Principal among these were lead telluride (PbTe), bismuth telluride (BiTe), bismuth antimonide (BiSn) and silicon-germanium (SiGe). From this list of materials, the BiTe material[10] was selected as one of the more promising candidates for power generation.

The construction sequence is illustrated in Figure 2. To start an ingot of BiTe is reduced to a fine power. Using appropriate doping techniques the BiTe powder is resolidified into wafer form with the wafers having the appropriate "n-type" and "p-type" configurations. Each wafer was then coated with a thin film of high temperature solder foil. The wafers were next inserted into a mini-punch and the small tinned bits stamped out. These bits were then inserted into an insulating matrix in an alternating "n"-"p" arrangment. A printed circuit mask was placed over the entire assembly and a thin copper shoe was deposited, for connecting the tinned bits. Removing the mask and excess copper, a module, as shown in the bottom of Figure 2 is obtained. The first modules produced had 15 junction pairs. These would be used to evaluate the concept. The next set of modules produced had 130 junction pairs. One of each type of module had a thin epoxy heat shield. This heat shield was applied by hand.

The thermoelectric properties of the BiTe material as determined by the manufacturer* are shown in Table 1.

Table I. Thermoelectric Properties of Bismuth Telluride

	n-type	p-type
Seebeck Coefficient:	198 $\mu v/°C$	230 $\mu v/°C$
Resistivity:	$9.4x10^{-3}$ Ω - cm	$14x10^{-3}$ Ω - cm

These values were determined at room temperature.

Based on these measurements, the open circuit voltage, from Equation 4, which can be anticipated for a temperature variation of 200°C is $V_{OC} = (198+230)x10^{-6}(200°) = 0.086$ V.

For 15 junctions the voltage would be 1.29 volts and for 130 junctions the voltage would be 11.18 volts. This would be more than ample to meet our 8.2 volts requirement.

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[10] *Rosi, F. D., "Thermoelectricity and Thermoelectric Power Generation", Solid State Electronics, Pergamon Press, 1968, Vol II.*

**The Teledyne Energy System of Timonium, Maryland fabricated the modules used in this research program.*

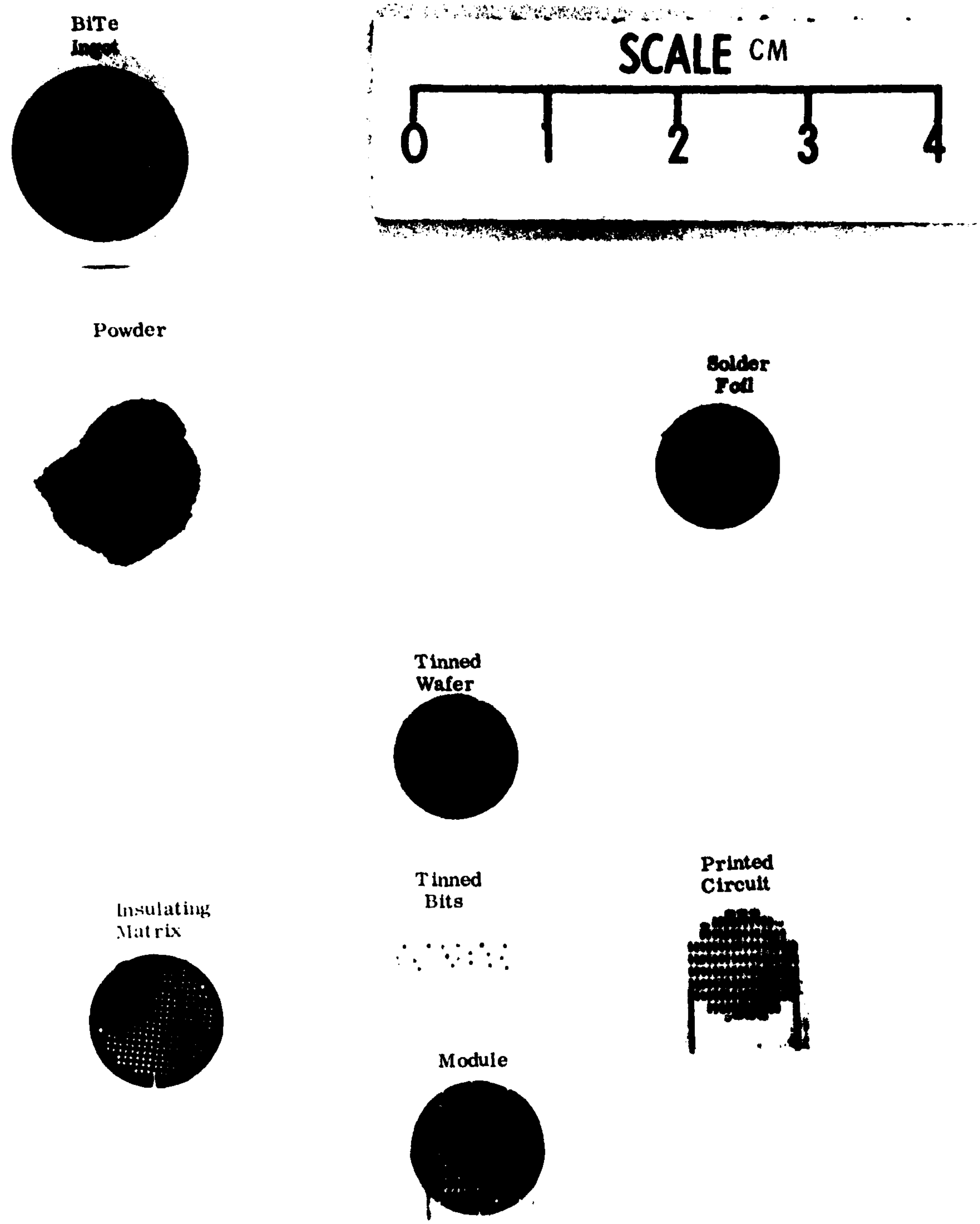

Figure 2. Construction Layout for Thermoelectric Module

The thermoelectric bits as punched out were 0.079cm in diameter and 0.0305cm thick. The internal resistance at room temperature was calculated from equation 8 to be

$$r = \frac{3x10^{-2}}{\pi(4x10^{-2})^2} \left[(9 + 14) \times 10^{-3}\right]$$

$$r = 0.137\ \Omega$$

When temperature is varied, the resistivity will also be subjected to variation. In a worst case which allows the resistivity to increase by 100% the internal resistance becomes approximately 0.3 Ω. For a module composed of 130 junctions the total internal resistance becomes 39 Ω.

By Equation 6, the power which the module composed of 130 junctions can develop is approximately

$$P = \frac{(11.2)^2}{2(39)} = 1.6 \text{ watts}$$

with 50% or 0.800 watts being delivered to the load. For an exposure time of 0.003 seconds an energy output of $2.4x10^{-3}$ joule can be expected, much more than is needed.

V. EXPERIMENTAL PROCEDURE

A. Test Apparatus

1. Construction.

To simulate an actual gun firing, and thus bring about the required environmental conditions, a contrivance known as a "closed vented chamber" was used. This device is basically a heavy walled steel chamber having several ports for the mounting of test specimens and/or instrumentation. The chamber was capable of operation up to 400 MPa. The pressure is controlled within the chamber by varying the amount of propellant that is used and the thickness of the associated blowout disk that is mounted in one of the ports.

A cross-sectional view of the chamber is shown in Figure 3. Two additional ports "C" and "D", not shown, are located perpendicular to the axis through ports "A" and "B" and are aligned 180° from each other.

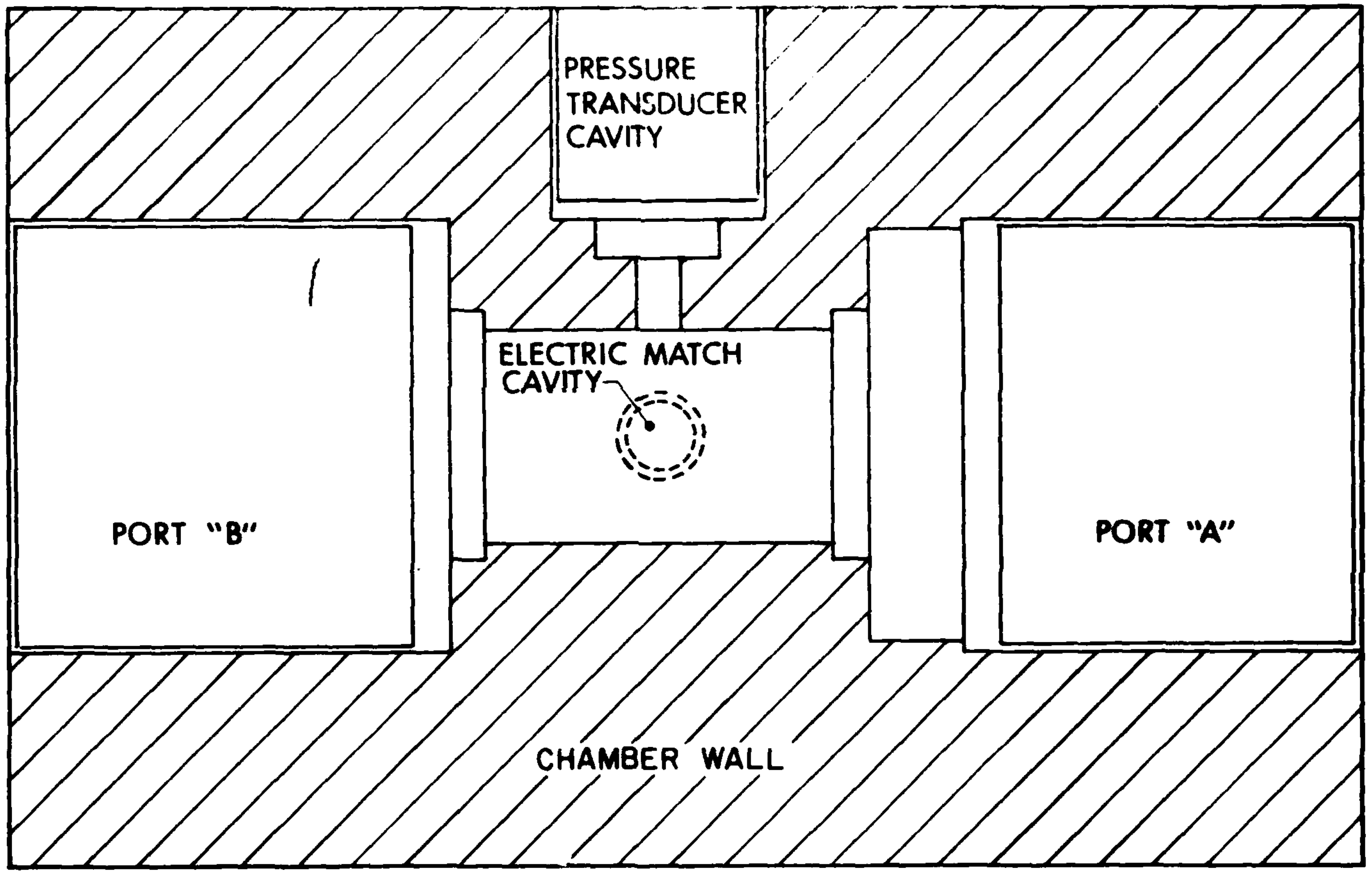

Figure 3. Cross-Sectional View of the Vented Chamber.

It is apparent that this device does not truly mirror small caliber gun firings. In actual gun firings the gases produced by the burning propellant cause the cartridge case to expand and force the warhead down the gun tube. As the projectile starts its motion the chamber volume increases causing a decrease in pressure. Simultaneously this volume-pressure alteration permits the burning rate of the propellant to increase. The pressure, therefore, continues to increase to some maximum value, which is generally reached a short distance from the origin of the rifling. Thereafter the pressure decreases. In the closed vented chamber there is no change in volume and the pressure increases steadly till the yield strength of the blowout disk is exceeded and rupture occurs. It is only the approximate risetime and the peak value of the pressure pulse associated with small caliber gun firinge that is simulated.

In addition, the thermoelectric module is to be mounted in the base of the warhead. When it is mounted in the test chamber it will not be subjected to the normal acceleration forces a gun fired projectile would receive.

Despite these shortcomings, the pressure and temperature produced within the test chamber should closely simulate those which are created within the first few milliseconds of an actual gun firing. They should provide an adequate test not only of the module's performance capability but also its ability to survive for a sufficient period of time.

2. Pressure Determination.

As mentioned in the section concerning Design Criteria the pressure profile of the M552 30mm round was to be simulated for these experimental tests. To accomplish this Ports "A" and "D" in the closed vented chamber were sealed off. Port "B" was adapted to accommodate the necessary blowout disk. An electric match is inserted through Port "C" and was the means used to initiate the propellant. The propellant was then loaded through the cavity located at the top of the chamber. This cavity was then sealed with a pressure transducer. The propellant used during these investigations was Dupont IMB 8261, a propellant in common usage in small caliber munitions. Several tests were performed in which the amount of propellant and thickness of the blowout disk were varied. Figure 4 shows the pressure profile which most closely matched the M552 round. This simulation was accomplished using 21.8 grams of propelalnt in conjunction with a 2.25mm thick "304" stainless steel blowout disk. All subsequent thermocouple testing was done under these conditions.

In these tests and all subsequent tests the data were recorded on magnetic tape and then processed by an on-line computer. The digitized data was then plotted. Simultaneously the actual data was plotted on an analog recorder.

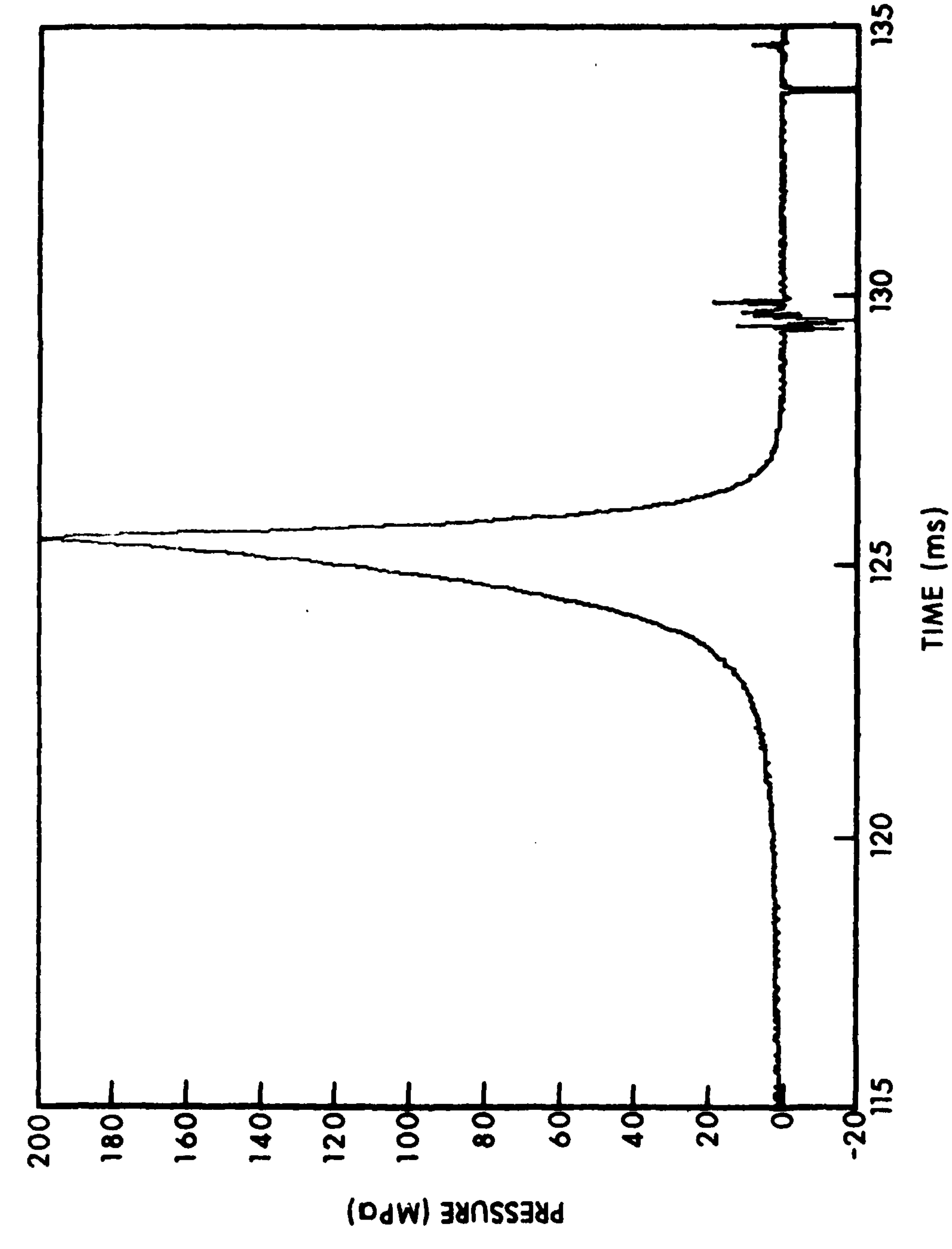

Figure 4. Pressure-time History: Test No. 4

3. Temperature Determination.

Having adjusted the pressure-time history within the vented chamber to match the M552 round, it is next necessary to determine the temperature of the environment generated within the chamber. To accomplish this objective a series of thermocouple tests were conducted using thin stainless steel disks.

Thermocouples were constructed from 0.025mm Chromel-Alumel wire. These were bonded to thin stainless steel disks whose thicknesses were 0.050, 0.125 and 0.25mm. The diameters of the disks were kept constant at 16mm. One of each thickness of the stainless steel disks was coated with a thermal epoxy heat shield. The thermal epoxy was applied by hand and its uniformity is subjected to question. The objective in evaluating these coated disks was to determine the temperature levels which could be expected should the need of a heat shield arise. The thermocouple specimes were then mounted in Port "A" of the closed vented chamber directly across from the blowout disk. The temperature tests were then conducted in the same manner as the pressure determination tests.

The maximum surface temperature of the disk within the chamber was then determined by using Fourier's steady state heat conduction equation. Fourier's equation is generally expressed as

$$q/A = - k \frac{\Delta T}{\Delta \chi} \tag{10}$$

where q/A = heat flux [cal/sec - m^2]

k = thermal conductivity [cal/sec - m-°C

ΔT = temperature gradient [°C]

$\Delta \chi$ = thickness of material [m]

Using the same lot of propellant, the same quantity, (21.8g), and an electric match as the initiator, the heat flux which is generated within the chamber is assumed to be constant. Under these conditions the temperature gradient across the stainless steel disks is directly proportional to their thicknesses. This can be expressed as

$$-k \frac{\Delta T_1}{\Delta \chi_1} = -k \frac{\Delta T_1}{\Delta \chi_2} = -k \frac{\Delta T_3}{\Delta \chi_3} \tag{11}$$

With the thermal conductivity being a constant of the material this expression reduces to

$$\frac{T_o - T_1}{\Delta x_1} = \frac{T_o - T_2}{\Delta x_3} = \frac{T_o - T_3}{\Delta x_3} \qquad (12)$$

where T_o = temperature on front surface of disk [°C]

T_1 = temperature measured by thermocouple [°C]

Δx = disk thickness [mm]

T_o is the temperature which the thermoelectric module will be exposed too during its testing.

Figure 5 and 6 show the type of data obtained in the thermocouple tests. The complete results of these tests are listed in Table II.

Table II. Thermocouple Response

Element: Chromel-Alumel 0.025mm Wire
Propellant: 21.8 g Dupont IMR 8261

Sample No.	Sensor	Maximum Pressure (MPa)	Thk. (mm)	Maximum Voltage Output (mv)	Temperature (°C)
1	SS.005	199	0.125	11.00	295
2	SS.002	200	0.050	17.65	430
3	SS.010	198	0.250	4.24	98
*4	SS.010	204	0.250	3.21	79
5	SS.010	204	0.250	4.47	109
*6	SS.005	199	0.125	6.17	151
7	SS.005	206	0.125	8.07	199
*8	SS.002	201	0.050	8.22	202

*Indicates coated samples

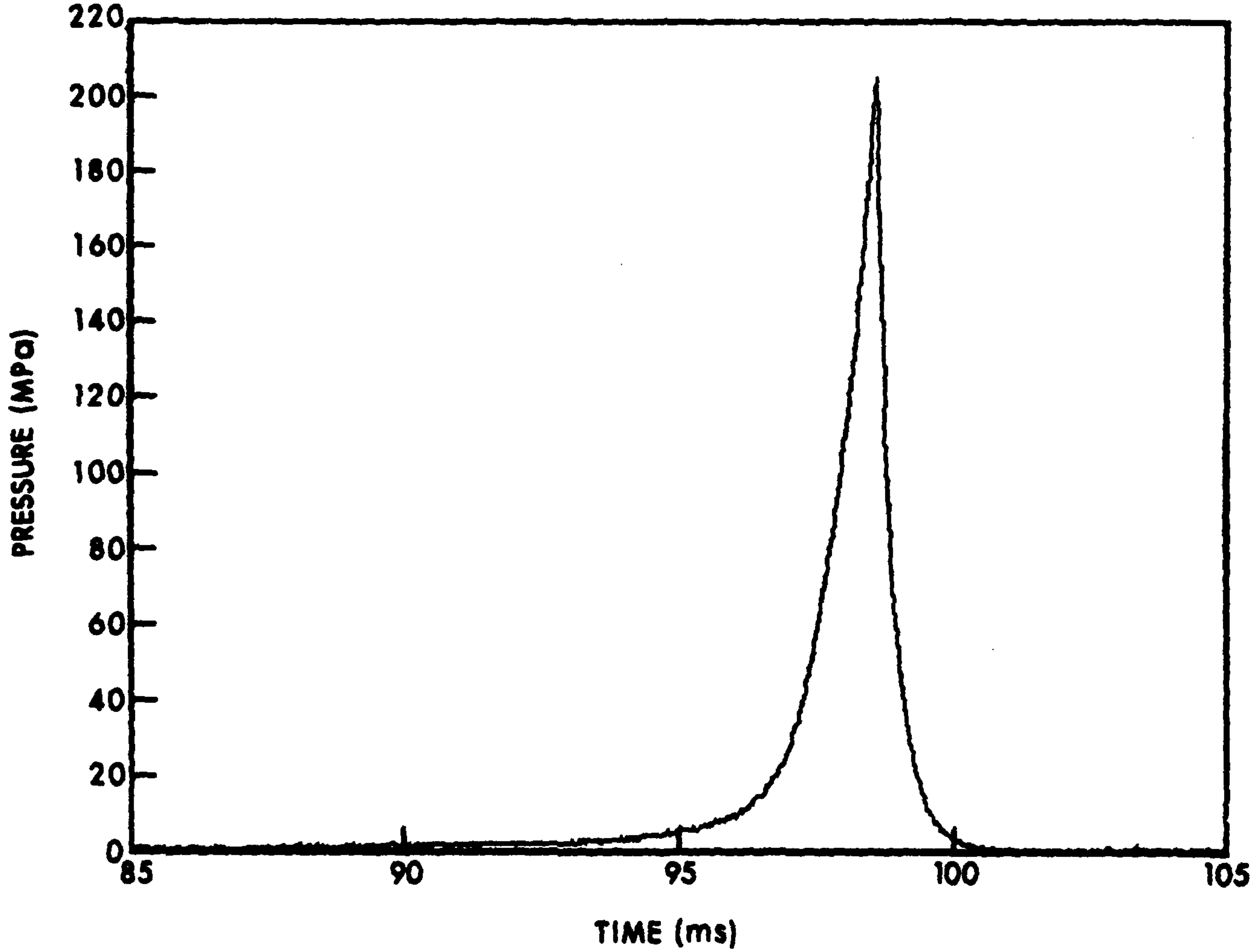

Figure 5. Pressure-Time History of Sensor SS.002 Test

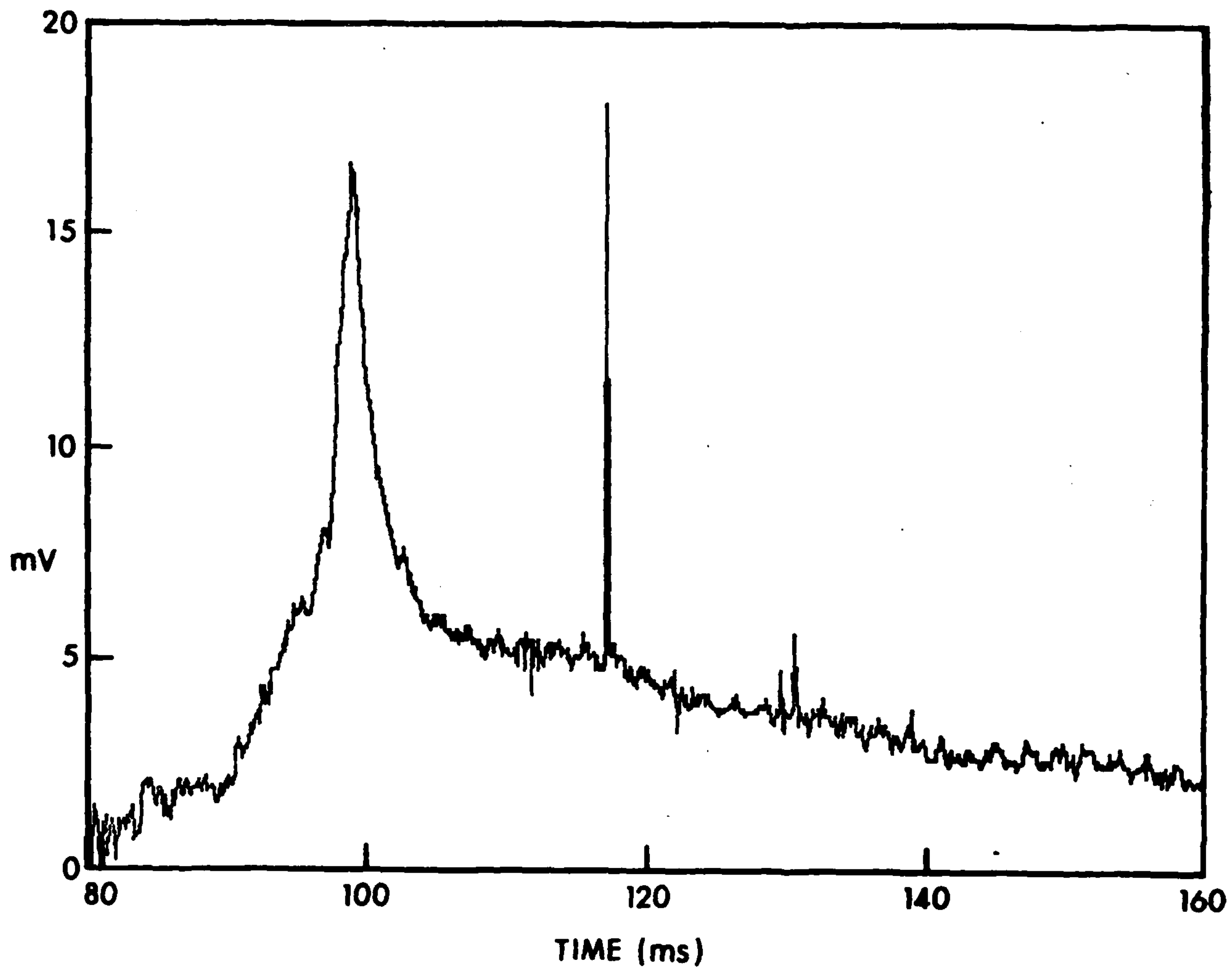

Figure 6. Voltage Output of Sensor SS.002

In Figure 7 the data are plotted as a function of disk thickness. One of the uncoated thermocouples at the 0.05mm disk thickness broke which is why there is only one data point at this thickness. The discrepancy at the 0.125mm thickness was due to a faulty bond between the disk and the thermocouple.

Using Equation 12, the average T_0 temperature is found to be 508 ± 16°C for the uncoated thermocouples and for the thermocouples with the thermal shields the average T_0 temperature is found to be 231 ± 8°C. Use of the thermal shield resulted in a 54% reduction in the value of the temperature the module would be exposed to.

It should be understood that the temperature values that were determined are only simple approximations. The actual temperatures are time dependent while the thermal conductivity is a function of temperature. Another point not considered was the variation in the thermocouple response with pressure[11]. Since it was the intent of the author to determine qualitatively the temperature within the closed chamber, a more exacting temperature determination will be left to those more involved in the fields of interior ballistics and heat transfer.

B. Thermoelectric Module Tests

Two module configurations were fabricated. The first set of modules contains 15 junctions. The second set contained 130 junctions. One of each type of configuration was coated with a thin thermal epoxy heat shield.

Like the thermocouples, each module was inserted into Port "A" of the vented chamber. They were then exposed to the pressure and temperature environment generated by the ignition of the 21.8 g. of propellant. The output of each module was recorded on magnetic tape. Figure 8 and 9 are the recorded data from one of the 15 junction module tests while Figures 10 and 11 are the recorded data from one of the 130 junction module tests.

VI. TEST RESULTS

A complete listing of the modules tested and the results obtained are given in Table III. The number in parenthesis after the module identification number is the number of junctions the module contained. Samples 2 and 6 were open circuited and therefore not tested.

There was a noticable drop in the intensity of the pressure pulse for the tests on samples 4 and 5. This is attributed to the variation in the blowout disk assembly. All the previous tests had been conducted with a single 2.25mm thick stainless steel disk. These

[11] *Bundy, F. P., "Effect of Pressure on EMF of Thermocouples", General Electric Research Laboratory, Schenectady, New York.*

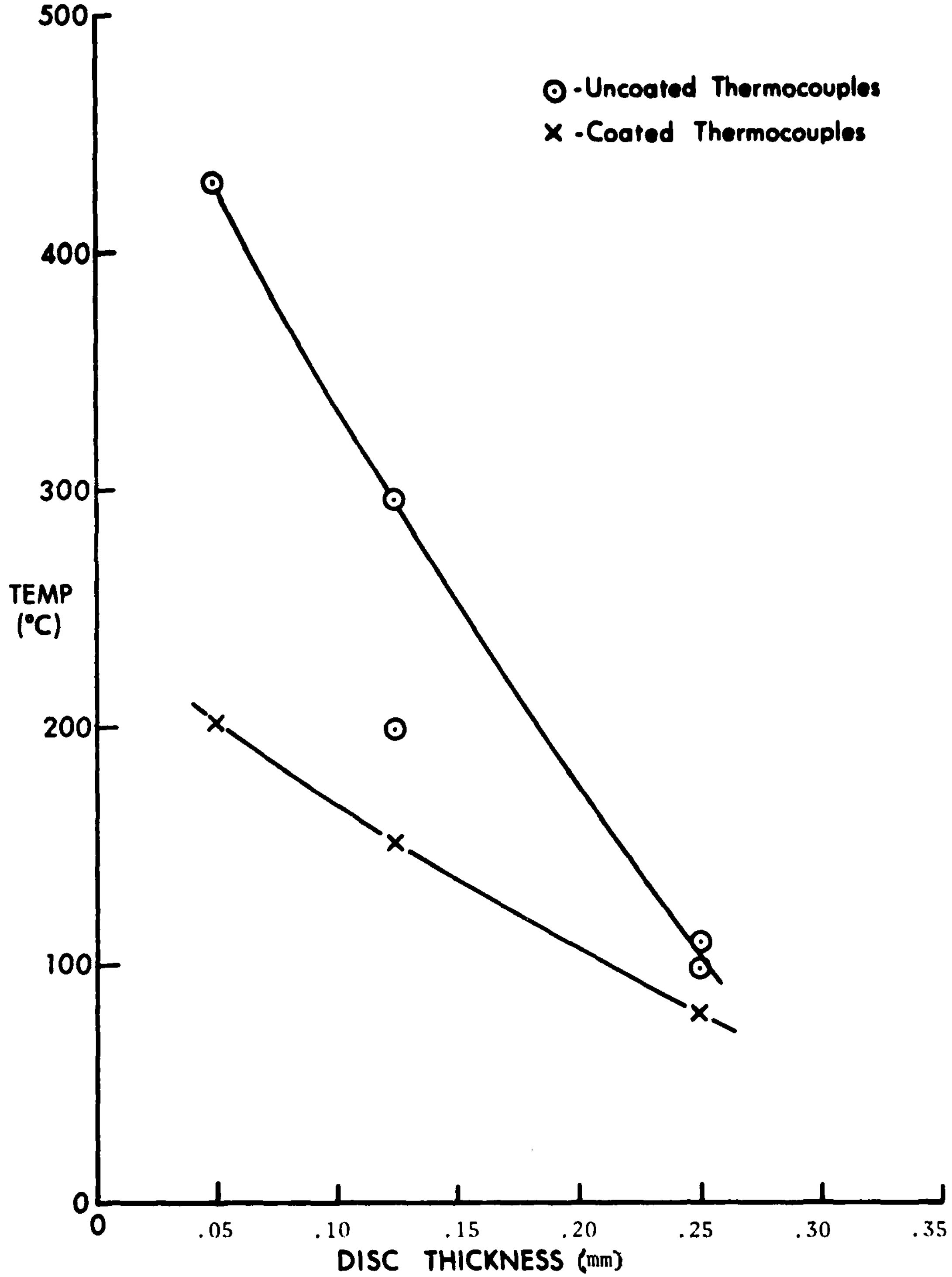

Figure 7. Temperature Output: Chromel-Alumel Thermocouples

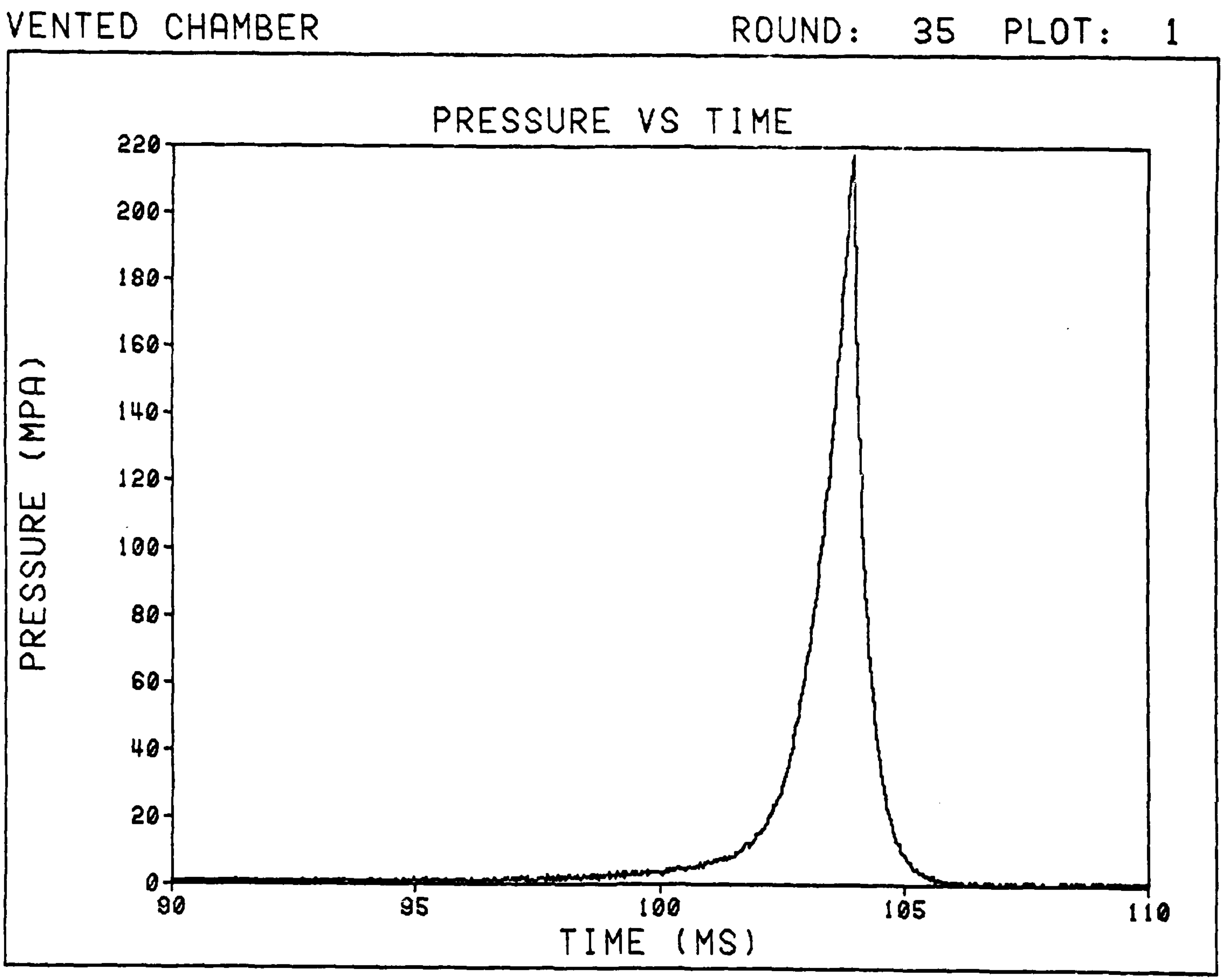

Figure 8. Pressure-Time History of Thermoelectric 15 Junction Module No. 1.

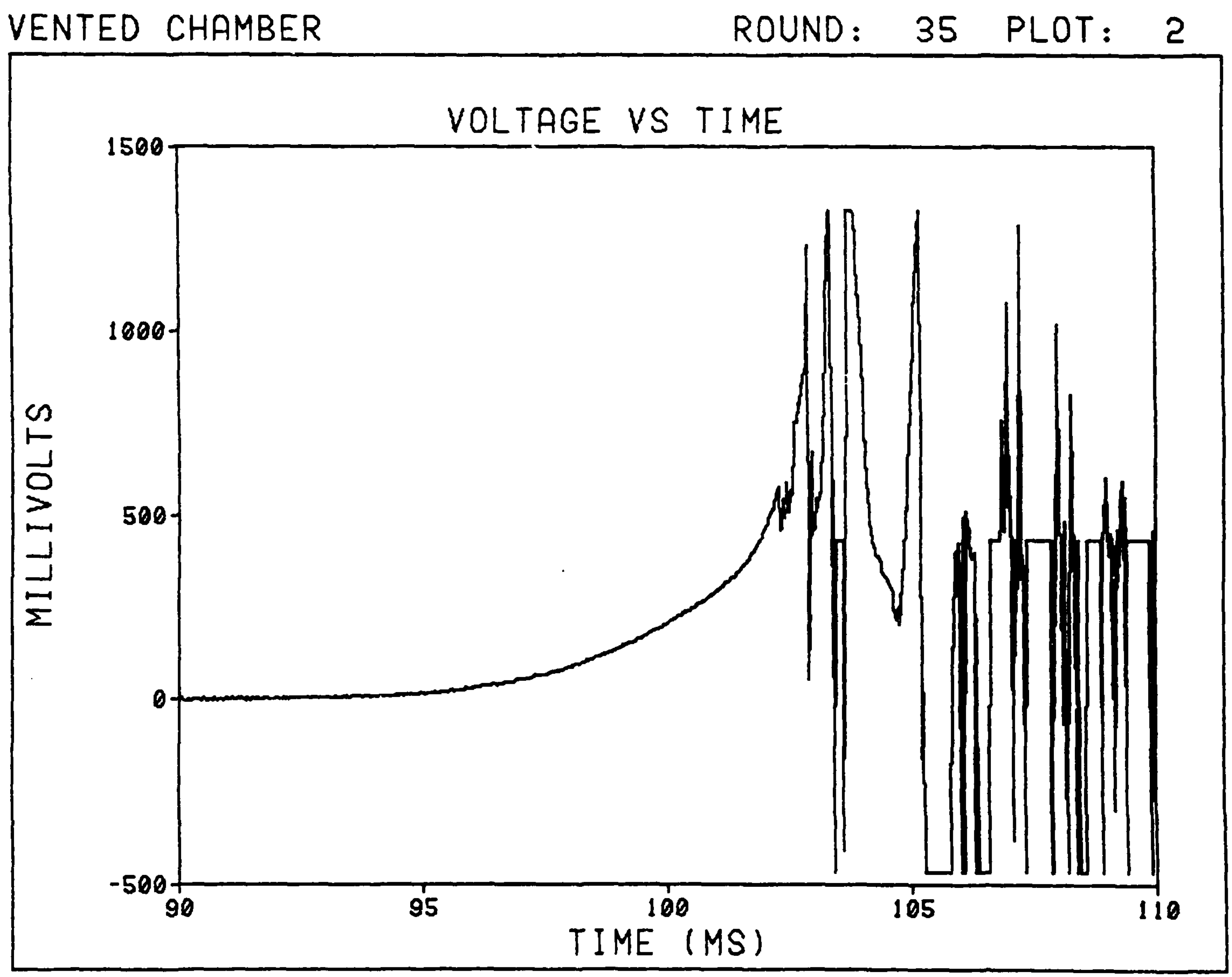

Figure 9. Voltage Output of Thermoelectric 15 Junction Module No. 1.

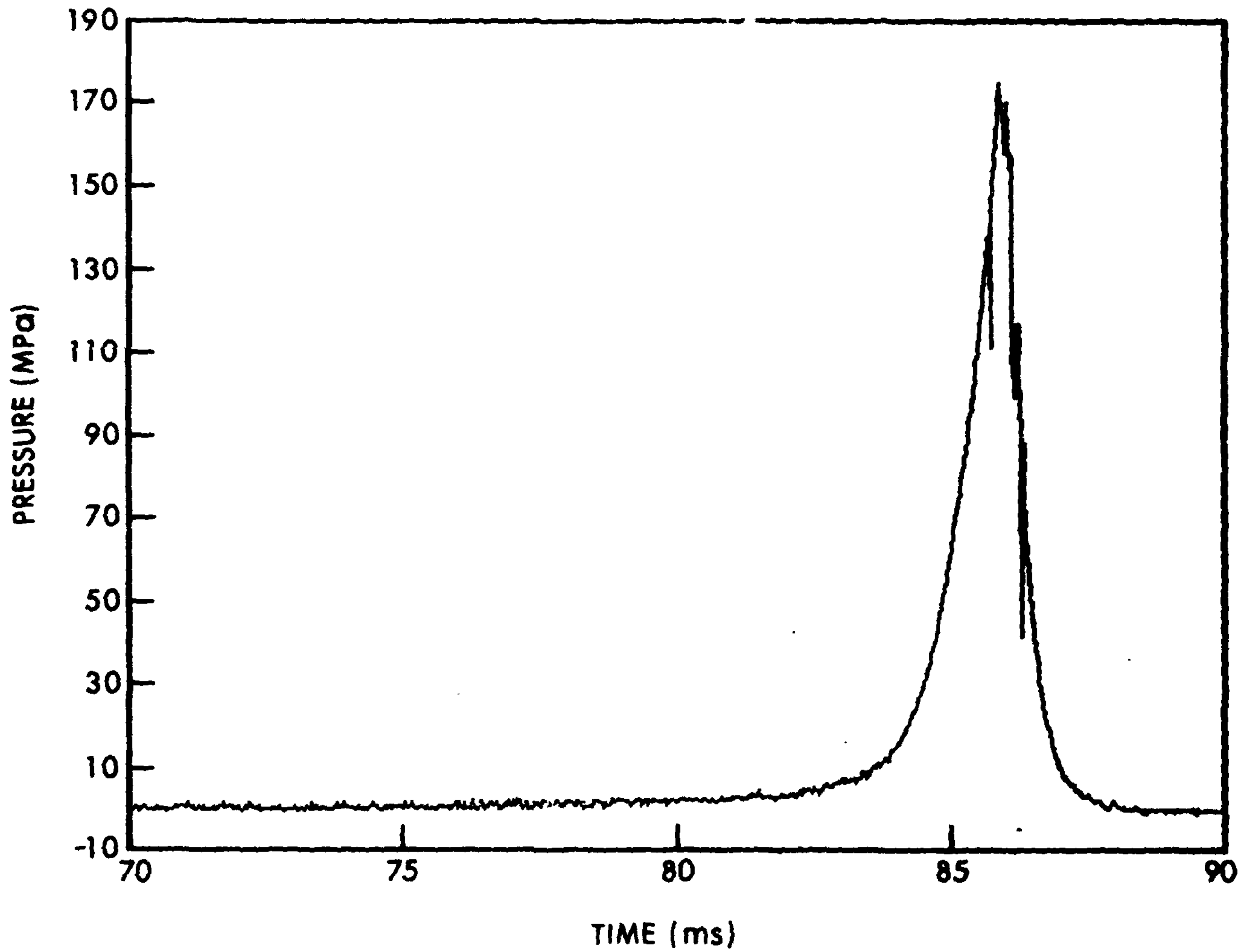

Figure 10. Pressure-Time History of Thermoelectric 130 Junction Module No. 5.

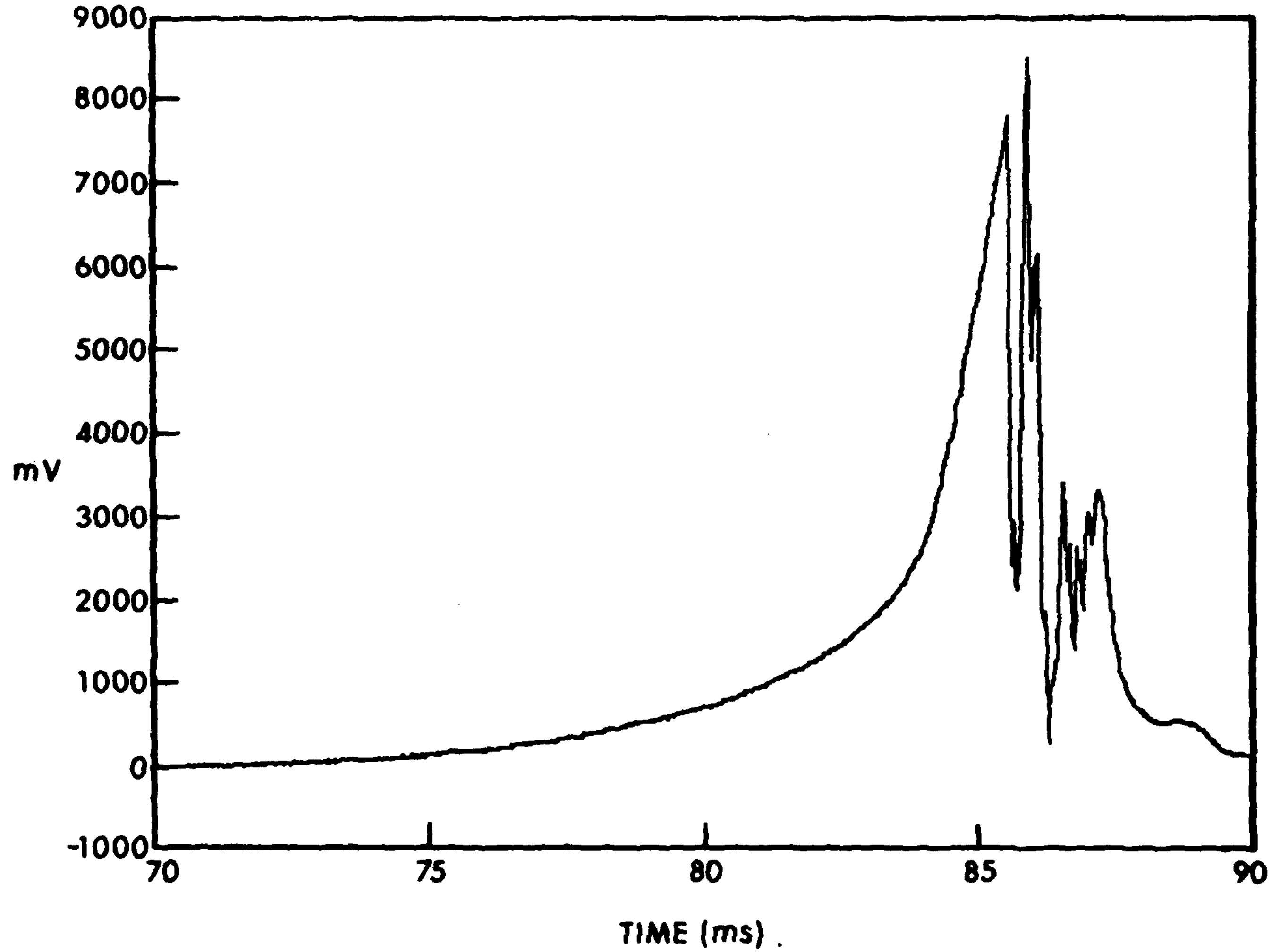

Figure 11. Voltage Output of Thermoelectric 130 Junction Module No. 5.

Table III. Thermoelectric Module Response

Material: Bismuth Telluride
Propellant: Dupont IMR 8261, Wt. 21.8g

Sample No.	Module ID.	Resistance Ohms	Pressure MPa	Output Volts	Output Volt/ Junction	Power** Watts
1	.002AA[15]	3.6	222	0.95	0.063	0.0625
2	.002AB[15]	-	-	-	-	-
3*	.002AC[15]	3.6	217	0.74	0.050	0.038
4*	.002AD[130]	9.8	191	1.30	0.010	0.043
5	.002AE[130]	12.5	169	8.37	0.064	1.40
6	.002AF[130]	-	-	-	-	-

*Indicates coated sample
**Theoretical power delivered for matched loads.

two tests were conducted using a blowout disk assembly of three 0.75mm thick disks instead of the one 2.25mm thick disk. This was necessitated by the fact that the 2.25mm disks were inadvertently used up in another series of tests. Since the thinner disks had been cut from the same bar stock it was felt that the three disk assembly would closely follow the response of the single 2.25mm thick disk. This, however, did not occur.

A second observable phenomena which was recorded was the inordinately long delay time between the initiation of the electric match and the 10% value of the risetime on the pressure pulse. This time varied between a minimum of 13 milliseconds and a maximum of 365 milliseconds. The thermoelectric modules show a long build up in temperature corresponding to the propellant burning. The maximum voltage pulse does correspond to the pressure pulse, however, and the delay does not appear to have any adverse effects on the tests themselves.

Use of the thermal epoxy heat shield produced significantly lower output voltage. For the modules composed of 15 junctions a reduction of 22% was observed and a reduction of 84% was observed for the modules with 130 junctions. This variance is attributed to the method of applying the epoxy by hand without any uniformity of application.

Examination of each module after testing showed that all units were open circuited. This is believed to be caused by the relief of the pressure pulse pulling the metallic strip loose from the semiconductor elements.

The calculated voltage output for a temperature variation of 200°C was 1.3 volts for the 15 junction module and 11.2 volts for the 130 junction module. This was based on an open circuit voltage of 0.086 volt per junction. The measured output voltage was 0.95 volt for the 15 junction module and 8.37 volts for the 130 junction module. This corresponds to an open circuit voltage of 0.063 volt per junction in the case of the 15 junction module and 0.064 volt per junction in the case of the 130 junction module. This value was approximately 27% lower than the calculated value.

The internal resistance of the modules also varied from the calculated values. This can be attributed to the contact resistance in the junction and to possible shorting between adjacent thermo-elements.

VII. CONCLUSIONS

It may be concluded even from this small number of test samples that a thermoelectric power generator utilizing the hot propellant gases is feasible. The voltages which were measured while lower than the calculated values were still significant.

The module remained in tact for an appreciable period of time, 3 milliseconds. The time period could possibly be extended for the shorter pressure pulses associated with gun launch.

The use of a heat shield appreciably reduced the thermoelectric voltage output in these tests. The surviability of the unprotected modules appeared to be adequate, therefore the use of a heat shield may not be requried.

The basic theoretical relationships used to design the module appear to be accurate as a first approximation. However, changes in resistivity and thermal conductivity of the BiTe material with temperature and pressure have not been properly taken into account. Hence, there is a need to better quantify these material properties under experimental conditions.

VIII. RECOMMENDATIONS

Future developmental work on this concept is recommended. This work should include the determination of pressure effects on the thermal conductivity of the thermoelements and acceleration effects on module performance. Other materials, such as SiGe, should be investigated for use in the thermoelectric module. Actual thermo-electric modules should be fabricated and tested in gun firings. Techniques to build more cost effectively should be studied. Mil-Spec testing of the modules should be done as well as aging tests

Through such research efforts a thermoelectric power generator can be developed for use not only in large and small caliber munitions but also one which can be used in remote, unattended and hazardous locations.

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